CMS Internal Note

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Simulation of Cosmic Muons in CMS - Manual and first Results

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Abstract

This document is intended to describe the cosmic simulation package available in CMKIN. In this approach, cosmic muons are generated on the surface of the earth and then propagated to the surface of the CMS detector. During the propagation phase the energy loss from rock and the walls of the CMS underground area is simulated. The cosmic muon simulation stops at this point. The muons are written to a standard CMKIN ntuple and the rate of the muons arriving at the surface of the CMS detector is calculated.

In addition to the description of the features of the simulation, of the code, and of the main control parameters, this document contains a few plots for the following purposes: validate the geometry of the CMS underground area, show the kinematic features of cosmic muons, and understand the consequences of the energy loss.

1 Primary Cosmic Muons

Muon as they are arrive at the surface of the earth are referred to as primary muons in the following. These muons are produced in air showers initiated by very energetic particles coming from space. The simulation of the primary cosmic muons follows closely the description in Ref. [1].

◇ Muon Type
Because the initial cosmic rays are stable charged particles or nuclei, the muons produced in the air showers yield a typical ratio of positive to negative charge. This ratio is $n_{\mu^+}/n_{\mu^+} = 1.2$ in this simulation. The slight energy dependence of this ratio is not taken into account.

◇ Energy Spectrum
The simulation of the energy spectrum is done according to the following approximate formula.

$$\frac{dN_\mu}{dE_\mu} \approx \frac{0.14\ E_\mu^{-2.7}}{\mathrm{cm}^2\ \mathrm{s}\ \mathrm{sr}\ \mathrm{GeV}} \times \left(\frac{1}{1 + \frac{1.1\ E_\mu\ \cos\theta}{115\ GeV}} + \frac{0.054}{1 + \frac{1.1\ E_\mu\ \cos\theta}{850\ GeV}} \right) \tag{1}$$

For technical reasons, the dependence on $\cos\theta$ is simulated for eleven discrete values of $\cos\theta$. It has been verified that no binning effect is visible in the energy spectrum.

◇ Angular Distributions
A good way to describe angular properties of cosmic muons is the choice of cylindrical coordinates with the symmetry axis being the y axis (vertical axis), not the z axis (beam line) as in case of detector coordinates. The muon rate follows a $\cos^2\theta$ distribution and ϕ is distributed in a flat way. The curvature of the earth, relevant for almost horizontal muons, is not taken into account in this simulation.

◇ Muon Starting Point
All muons start to exist in a square on the surface of the earth. The size of this square is chosen in a way that the muon distributions for a given angular range are unbiased. The starting point of the muon is updated during the propagation, as described in the following section.

◇ Muon Starting Time
The starting time t_0 is the time when the muon starts to exist. Because the cosmic muons arrive at the earth randomly, the distribution of t_0 is flat. In contrast to the starting point, the starting time is not updated during the muon propagation.

2 Cosmic Muons at CMS

On the way from the surface of the earth to the surface of the CMS detector, the cosmic muons have to pass the material underground. In order to model the effect of energy loss of the muons, the muon is propagated trough the material of the CMS underground area. The code contains a simplified description of the CMS underground area including the foundations of the surface buildings.

◇ Geometry Description
The CMS underground area is described in three dimensions with three types of material: air, rock and wall. The actual dimensions have been extracted from drawings [2] which have been used to construct those facilities. In particular, a good description of the material above the CMS detector is needed for a realistic simulation of the energy loss of cosmic muons. Examples of various views are shown in Fig. 1 and Fig. 2.

◇ Energy Loss
Employing the geometry description of the CMS underground area, the energy loss is simulated by propagating the muon through the material. During this propagation, the traveling length of the muon trough each material is summed up from which the energy loss is calculated with following expression.

$$E_\mu = (E_{\mu,0} + \epsilon)e^{-bX} - \epsilon \quad \text{with} \quad \epsilon = \frac{a}{b} \tag{2}$$

X is the thickness of the material and the parameters a and b can be found for a material called “standard rock” for $E_\mu = 10$ GeV in Ref. [1]. In this particular simulation, the energy loss is calculated with identical parameters for two types of material: for rock and for the walls made of reinforced concrete. This approximation is justified, because the densities of both materials are similar, $\rho \approx 2.7\ \mathrm{g\ m}^{-3}$. The energy loss in air below the surface of the earth is neglected. Effects due to energy loss are discussed in some detail in the last section.

◇ **End of Simulation**
After the muon has arrived at the surface of an cylinder around the CMS detector (parameters TAKE_R and TAKE_Z see Tab. 1) and the energy loss is calculated, the cosmic muon simulation stops and the muon information can be passed to the CMS detector simulation. Individual events are saved in a standard CMKIN ntuple: the event record contains two lines. Line one is a comment line with information about the primary muon, and line two describes the muon arriving at the detector. Only the second muon will be picked up by the detector simulation.

◇ **Muon Rate**
The muon rate, as seen at the surface of a cylinder around the CMS detector, is calculated in the end of the event generation run and written to an text file. All the kinematic properties of the cosmic muons and the efficiencies due to energy loss or due to missing the detector surface are taken into account.

3 The Cosmic Simulation Package

The cosmic simulation code is available as a package of CMKIN [3]. After checking out the lated version of CMKIN, following files are available to run the simulation

$\mathrm{CMKIN}_\alpha_\beta_\gamma/$examples/make_ntpl_jobs/kine_make_ntpl_cosmic.com

$\mathrm{CMKIN}_\alpha_\beta_\gamma/$examples/make_ntpl_jobs/kine_make_ntpl_cosmic.run

$\mathrm{CMKIN}_\alpha_\beta_\gamma/$examples/make_ntpl_jobs/datacards/cosmic.txt

$\mathrm{CMKIN}_\alpha_\beta_\gamma/$src/kine/kicdes/cosmic.inc

$\mathrm{CMKIN}_\alpha_\beta_\gamma/$src/kine/kimain/ki_cos_main.F

$\mathrm{CMKIN}_\alpha_\beta_\gamma/$src/kine/kicosmic/ki_cos_init.F

$\mathrm{CMKIN}_\alpha_\beta_\gamma/$src/kine/kicosmic/ki_cos_fill.F

$\mathrm{CMKIN}_\alpha_\beta_\gamma/$src/kine/kicosmic/ki_cos_stat.F

After editing "cosmic.txt" and running the scripts "kine_make_ntpl_cosmic.com" and "kine_make_ntpl_cosmic.run", a ntuple, a text file, and optionally a histogram file are produced

$\mathrm{CMKIN}_\alpha_\beta_\gamma/$examples/make_ntpl_jobs/cosmic.ntpl

$\mathrm{CMKIN}_\alpha_\beta_\gamma/$examples/make_ntpl_jobs/kine_make_ntpl_cosmic.lis

$\mathrm{CMKIN}_\alpha_\beta_\gamma/$examples/make_ntpl_jobs/cosmic_geometry.hist

The most important parameters and constants, used in the code above, are summarized in Tab. 1. Some of the parameters can be changed in order to adjust the simulation to specific scenarios.

4 Summary and Discussion

The cosmic muon simulation consists of two main step: firstly, the muons with all their typical properties are generated on the surface of the earth. In the second part, the muons are propagated trough the material below the surface of the earth until they reach a cylinder around the CMS detector, and the energy loss is calculated.

As it can be seen from a comparison of Fig. 3 with Fig. 4, the effect of energy loss is visible. Obviously the energy spectrum is shifted to lower values, but also the angular distributions are affected: the muons tend to be more vertical, if the energy loss is simulated, because vertical muons have to pass less material than more horizontal ones. In the originally flat ϕ distribution a bump shows up in direction of the access shaft PX 56 (see also Fig. 2 (middle)), because the muons are provided with a corridor of air, where there is less material in their way. This effect becomes even stronger, if the muon energy spectrum starts at lower values.

Figure 5 shows maps of the points, where the muons hit the the surface of the cylinder around the CMS detector. Both plots show that the muons are typically coming from the top. This effect is stronger in case the energy loss is simulated. In addition, a region with higher density shows up below the access shaft.

For the parameters chosen for all plots, the muon rate reaching the cylinder around the CMS detector is about 8000 μ/s when the energy loss is simulated. Without the energy loss, the rate would be higher by a factor of five. However, the rates calculated should be understood as a rough estimate and therefore not be take too serious.

Acknowledgments

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References

[1] S. Eidelman et al. "The Review of Particle Physics" **Physics Letters B592, 1 (2004)**

[2] J.A. Osborne "LHC Project - Civil Engineering: Technical Drawings of the CMS Underground Area" **private communications**

[3] V. Karimaki et al. "CMKIN v3 User's Guide" **CMS IN-2004/016**

Table 1: *Control parameters used in the cosmic simulation package. The parameters are listed in anti-alphabetical order and are defined either in "cosmic.txt" or in "cosmic.inc". Parameters in fat print are intended to be changed via editing the data card COSM. Parameters marked with a * activate or deactivate parts of the simulation.*

name	default value	short description
Z_PX56	14000 mm	z position of central axis of PX 56
THEMIN	$0°$	minimal θ of generated muons ($0°$...THEMAX)
THEMAX	$45°$	maximal θ of generated muons (THEMIN...$90°$)
TAKE_Z	15000 mm	propagate until muon arrives at a cylinder with $\pm z$
TAKE_R	8000 mm	propagate until muon arrives at a cylinder with radius r
T0_MIN	0 ns	minimal starting time of the muons at the detector surface
T0_MAX	25 ns	maximal starting time of the muons at the detector surface
SF_O_E	88874 mm	surface of earth in respect to the center of CMS
P_STEP	10 mm	step size for particle propagation
PHIMIN	$0°$	minimal ϕ of generated muons ($0°$...PHIMAX)
PHIMAX	$360°$	maximal ϕ of generated muons (PHIMIN...$360°$)
MURATE*	1	calculate the muon arrival rate (0/1 = no/yes)
MPFRAC	0.545454545	fraction of muons with positive charge
EX_GEO*	0	examine the geometry (0/1 = no/yes)
EMUMIN	10 GeV	minimal energy of generated muons (> 1 GeV)
EMUMAX	1000 GeV	maximal energy of generated muons ($\approx 100\times$ EMUMIN)
EMIN_SEL	10 GeV	minimal energy of selected muons (recommended: = EMUMIN)
EL_PSF	1.0	scale factor for energy loss (0.0/1.0 = no/nominal)

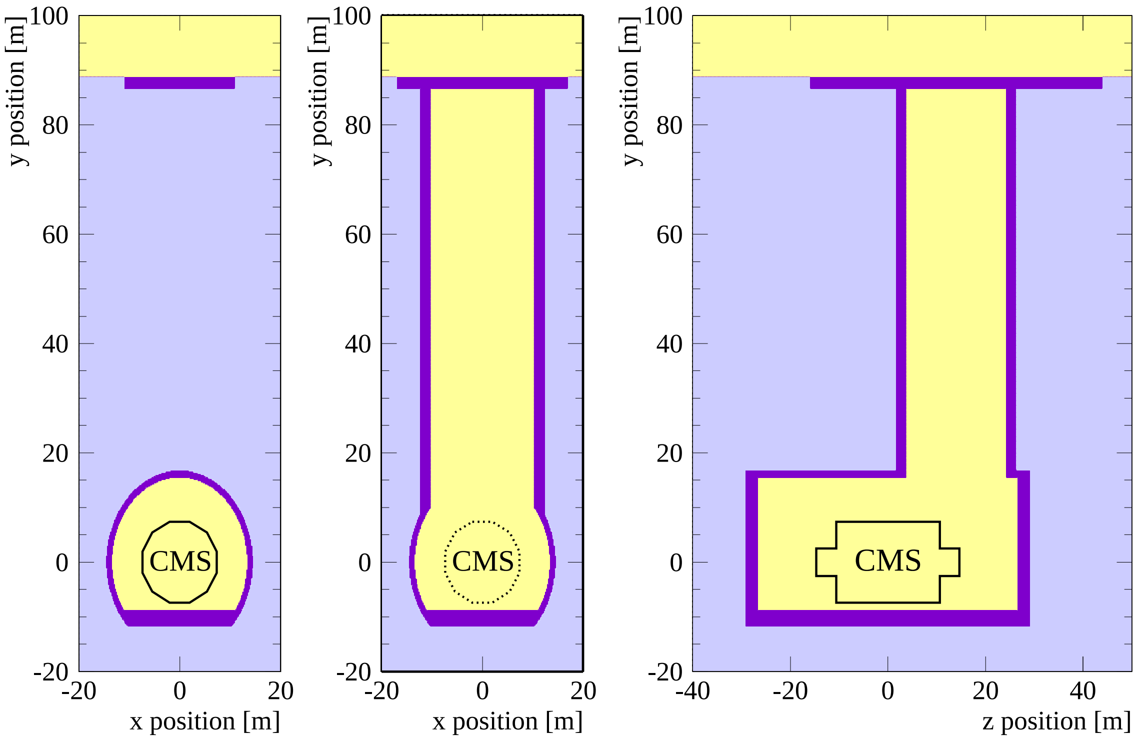

Figure 1: *Material distributions of the CMS underground area. Left: x-y-view at z = 0 m. Middle: x-y-view at z = 14 m (central axis of PX 56). Right: z-y-view at x = 0 m. Air is shown in yellow, rock in light blue and walls in dark blue. The CMS detector, sketched in black, is not included in the material description.*

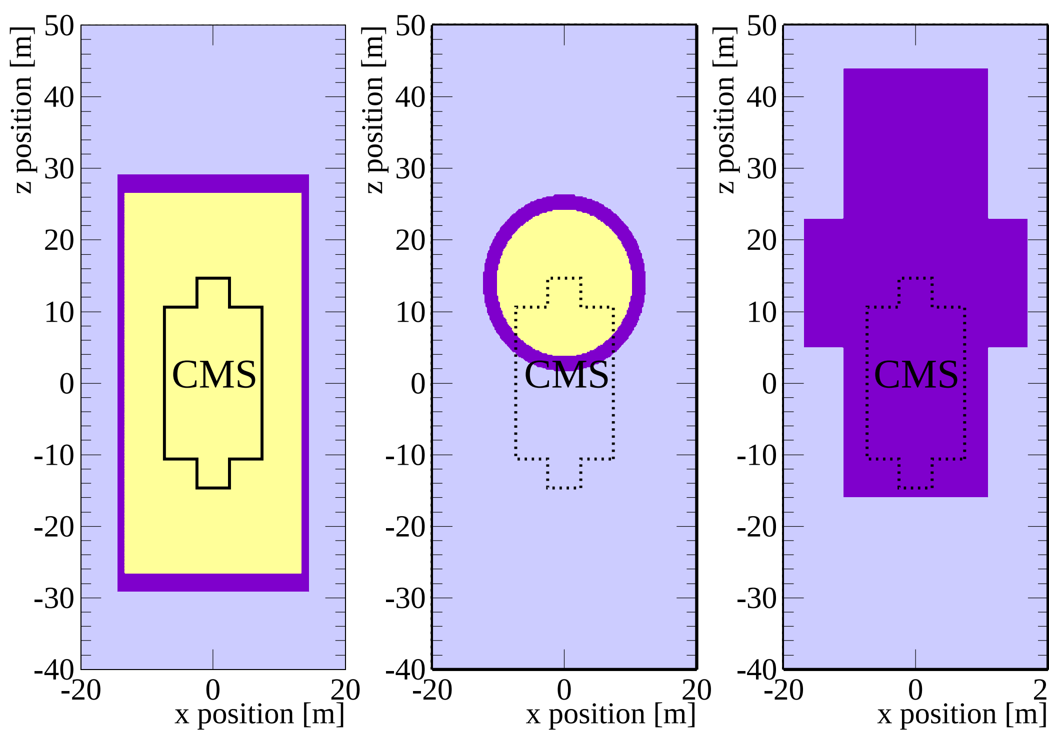

Figure 2: *Material distributions of the CMS underground area. Left: x-z-view at y = 0 m. Middle: x-z-view at y = 50 m. Right: x-z-view at y = 88.87 m (just below the surface). Air is shown in yellow, rock in light blue and walls in dark blue. The CMS detector, sketched in black, is not included in the material description.*

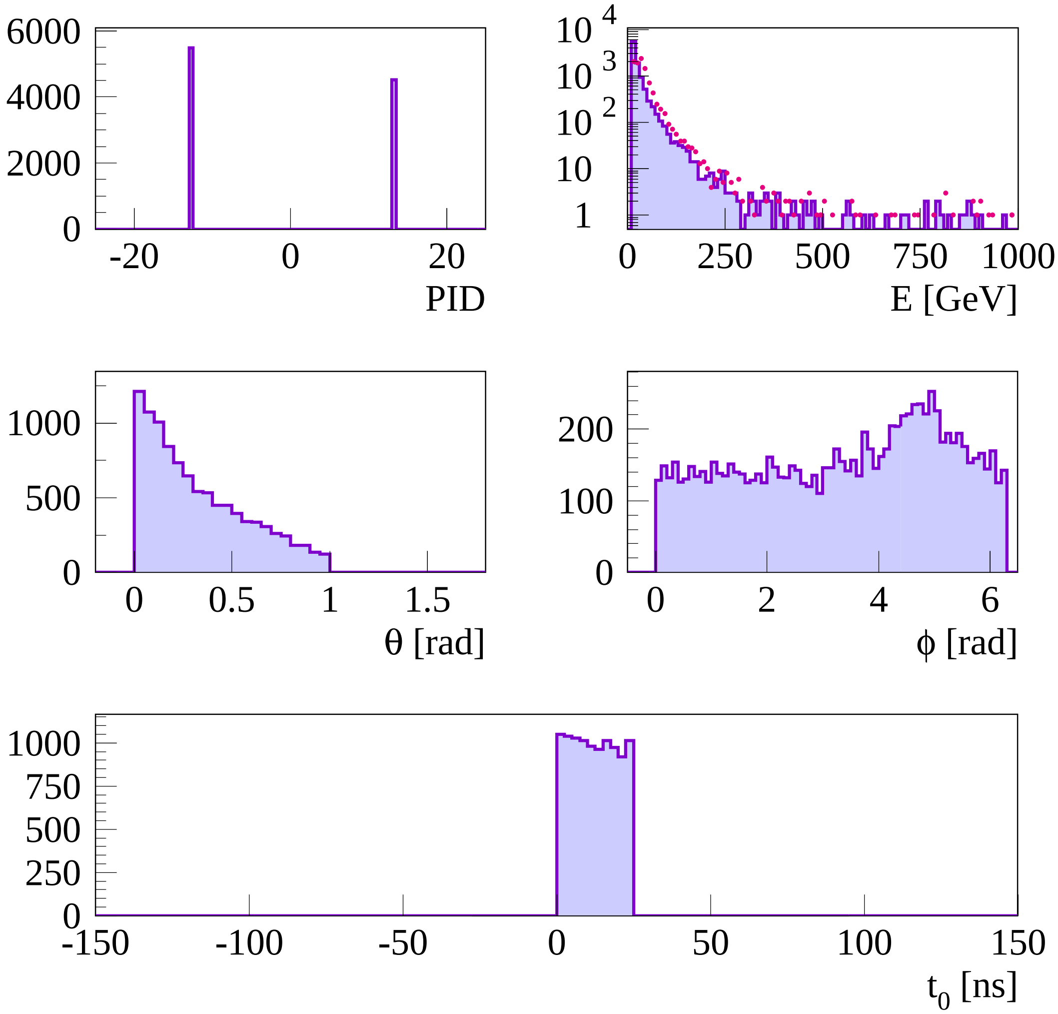

Figure 3: *Muon properties of cosmic simulation including energy loss. The particle identification number PID is -13 for* μ^+ *and +13 in case of* μ^-*. In the energy distribution the minimal energy is 10* GeV*, and the red dots describe the energy spectrum not including the energy loss.* ϕ *and* θ *are the usual angles of cylindrical coordinates, but with the vertical axis* y *as the symmetry axis.* t_0 *is the starting time of a muon on the surface of CMS.*

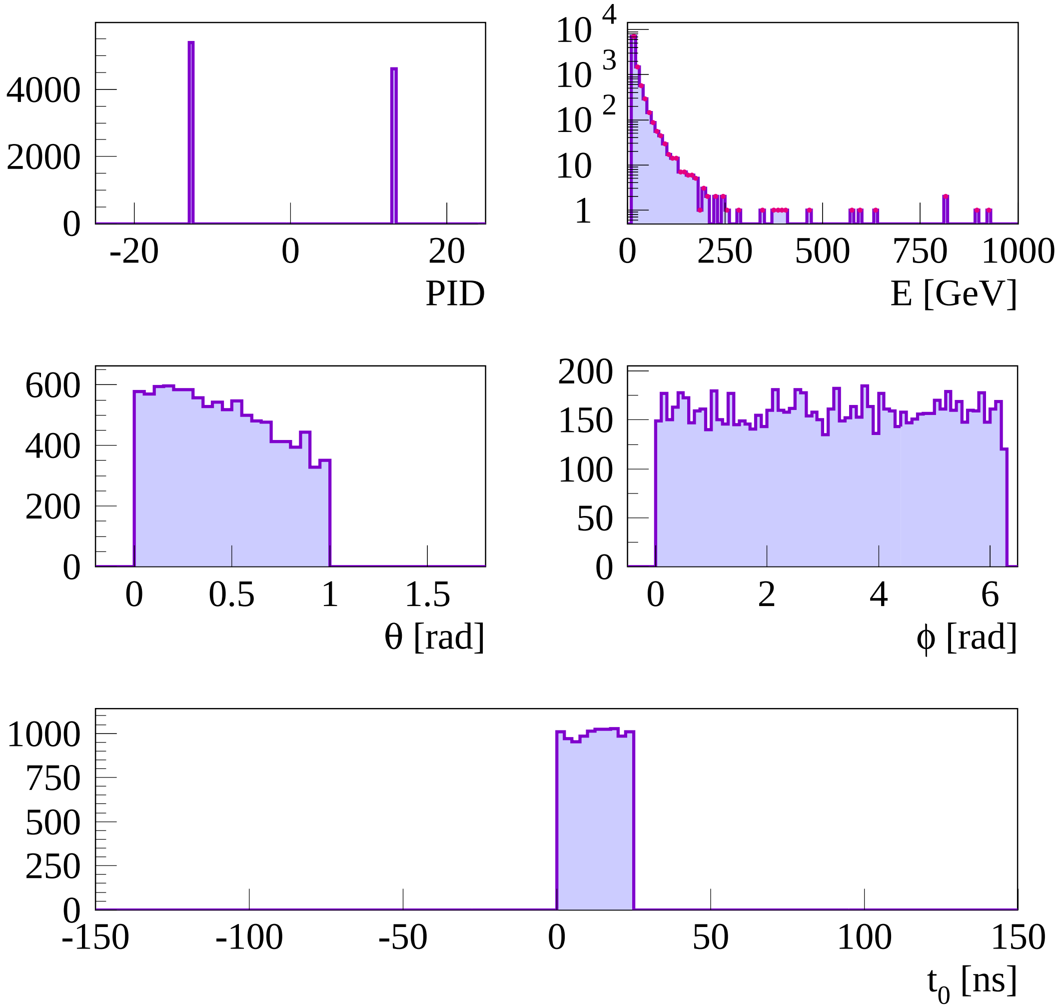

Figure 4: *Same as Fig. fig:kine1, but without simulation of the energy loss (EL_PSF = 0.0).*

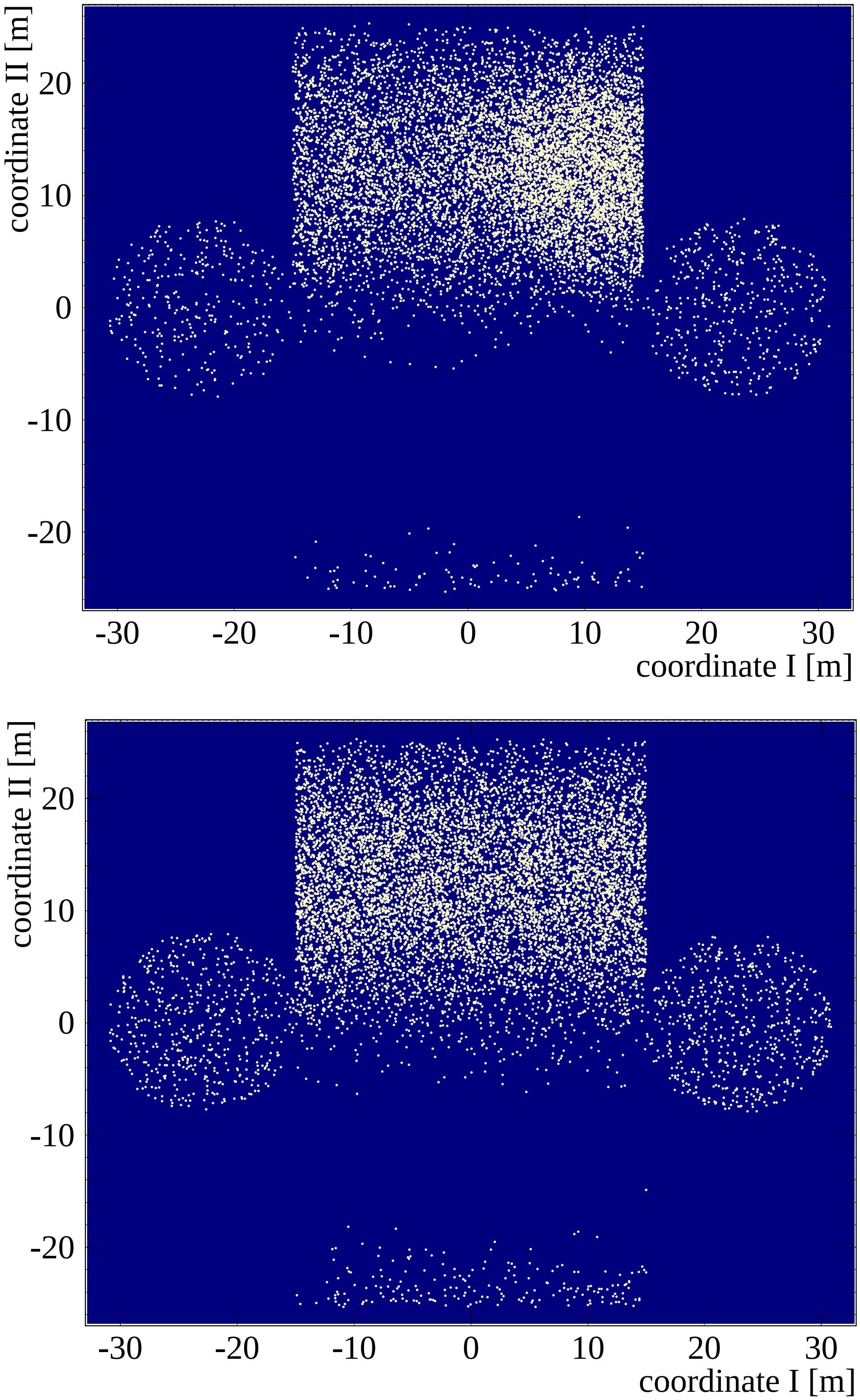

Figure 5: *Muon entry point position. Top: simulation including energy loss. Bottom: simulation without energy loss. The surface of a cylinder around the CMS detector is plotted in a plane: in case of the disks, coordinate I and coordinate II correspond to x and y. In case of the rectangle, coordinate I corresponds to z and coordinate II corresponds to $r\phi$ with r = 8 m. Examples: x = 0 and $y = r \Rightarrow$ coordinate II $\approx$ 13 m ; $x = -r$ and y = 0 $\Rightarrow$ coordinate II = 0 m ; x = 0 and $y = -r \Rightarrow$ coordinate II $\approx$ -13 m.*